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PANORAMIC WINDOWS IN AEROPLANES? – VISION OR FANTASY

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Abstract

The considered theme affects a wide range of the different technical but also physiognomic divisions inside an aeroplane. On the side of structural principles the use of none loaded panes, exclusive of internal over-pressure, as well as an interieur without a life transmission of the surround outlook are important boundaries for the actual investigations. It began with the question: How could retrofit structural designs better handle with fuselage openings than conventional plate structures involving skins? Of course important adaptations are expected - for example to the 100 years old approach of the quasi two dimensional framework. Note, it is state of the art in architecture.

Additional requests are such as possible derivations of a well known framework by a bionic driven design, in the more general sense of biomimetic. If its methods are able to describe, then the research shall be extended to the application for windows up to emergency exits as well as passenger doors.

1. THE APPROACH

1.1. In general

With this theme it is mandatory to arrive in the field of geodesic structures. Especially research groups in the aeronautical sector consider such structures since decades, e.g. FIG 1.. Each ambition has lead to the extreme light weight plate structures, their behaviour in buckling or the more homogeneous directional stiffness by using stiffeners.

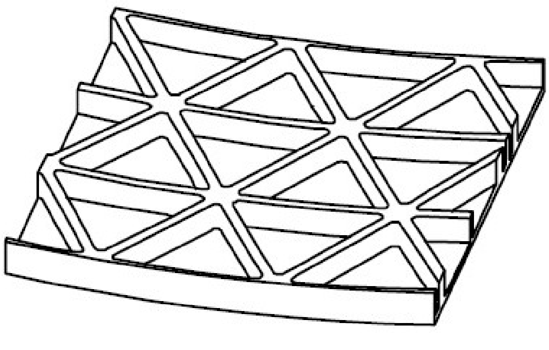


FIG 1. Integral Airframe Structures (IAS) by NASA/ Boeing about 2000 7

About 80 years ago it was usual to have two design parts of aeroplanes with frameworks. Of course not one of them was operated in pressurised services. The skins were only a flow control in the sense of aerodynamics, e.g. FIG 2..

FIG 2. Vickers Wellington

FIG 3. Polar station – geodesic dome, with skin elements

The architecture and construction comprise a great field of structural frameworks. Especially bridges or halls like domes made of steel span large distances by the use of frameworks. These are loaded by weight at first. Simultaneously it gives the chance of great transparency. This principle has been used since about 200 years, actual e.g. FIG 3. and FIG 4..

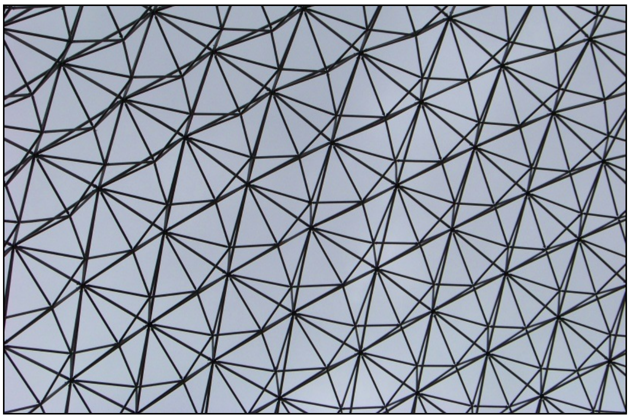


FIG 4. An impression of a 3D framework, the BioSphere Museum in Montreal with two quasi skins

FIG 5. Lloyds building in London, a 2D framework

One popular example is given by the Lloyds Building in London. Here is shown an advantage of understanding. The framework pauses with elements in some regular positions, but what is the difference in understanding? This design substitutes the conventional orthotropic frames of a vertical building hull by a framework. The principle of plate structure is switched.

1.2. Requirements by interieur

For a more comfortable and eventful flight cabin windows were enlarged step by step over the last years. But it does not seem that a change could be expected in the conventional understanding – windows are structural disturbances. Ignoring this a short hypothetical investigation has shown that a desire exists for really enlarged windows. This statement bases on a questionnaire, which was filled out by 10 ordinary people. So it is not representative but it can indicate a direction for further investigations.

The cabin package discusses a qualitative equality of each seat position in an arrangement of the business class. Every passenger shall be able to look relaxed outside the aeroplane. The eye points have to lay in a pattern without a hidden view to the windows.

At least the author dominated the basic principle of the social contacts inside a cabin. The most important point is the talk with strangers beside the privacy. It needs a design approach for a communicative ambience, making it easy to look at the neighbour or set sensitive signs of desired private sphere. The colours, materials and different shapes shall welcome the single passenger to introduce himself. There is no possibility for total encapsulation.

In addition the structural opportunity shall be harmonised with the psychological constitution of passengers as well as the expected and desired impressions by the flight itself. It leads to the design space for the window area. In parallel new challenges could be formulated in the point of the assumed dimensions for a single pane.

2. BARS LIKE A SHELL

2.1. In principle

Generally shells effect in two structural ways, in plane and out of plane. The described approach assumes a 2D framework in the 3D space. All requests out of plane have to be handled by the lateral beam strength. But in plane the membrane loads affect the framework itself made of single bars.

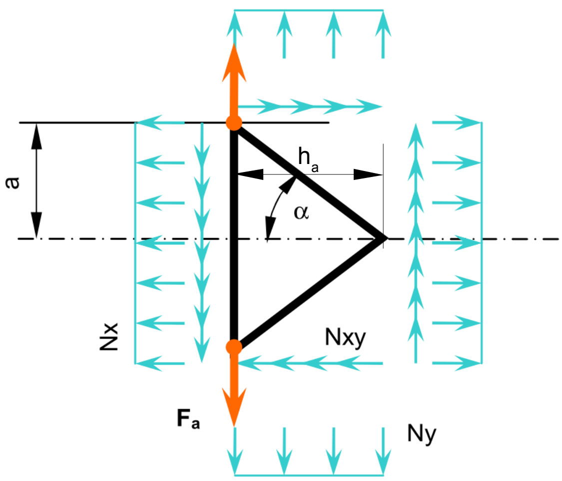


FIG 6. Single basic cell of a regular framework, e.g. F_a

(1) $F_a(Nx) = -Nx \cdot a \cdot \tan\alpha$

(2) $F_a(Ny) = Ny \cdot \dfrac{a}{\tan\alpha}$

(3) $F_a(Nxy) = 0$

This is extended to a combination with the classic laminate theory, eq.(4) to (6). Today it describes the rod loads for three independent helical directions in [3], including the longitudinal and circumferential orientation. The heights of triangles h_i determine the load concentration for framework elements.

(4) $\vec{n} = \vec{\sigma} \cdot t$

(5) $$\bar{T} = \begin{bmatrix} \cos^2\alpha_1 & \cos^2\alpha_2 & \cos^2\alpha_3 \\ \sin^2\alpha_1 & \sin^2\alpha_2 & \sin^2\alpha_3 \\ \frac{1}{2}\sin 2\alpha_1 & \frac{1}{2}\sin 2\alpha_2 & \frac{1}{2}\sin 2\alpha_3 \end{bmatrix}$$

(6) $$\begin{bmatrix} n_{\|1} \\ n_{\|2} \\ n_{\|3} \end{bmatrix} = \bar{T}^{-1} \cdot \begin{bmatrix} n_x \\ n_y \\ n_{xy} \end{bmatrix}$$

(7) $\vec{F}_i = \vec{n}_{\|i} \cdot \vec{h}_i$

Another way is shown using smeared properties. So the 2D framework also called lattice shell is analysed like a general anisotropic shell. It is the analogous procedure as used for the conventional orthotropic fuselage panels. This enables the evaluation of the global behaviour for an assembled curved panel or shell. It is assumed that the structural nodes are not discontinuities for no helical orientation.

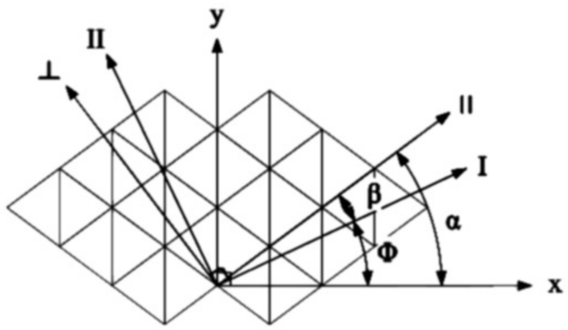


FIG 7. Nomenclature for the extended CLT-approach

In 7 a similar method is introduced as more abstract as above. It is prepared to solve one goal optimisations in case of buckling, shell stiffness or strength. The considered type of structural applications is the field of spacecraft, especially launch vehicle interstage. Thereby some analytical restrictions are applicable, e.g. the use of one single load case – axial compression. This represents the highest local compression load by a bending moment too. So on the one hand the used formulations exceed the possibilities of the cell approach, on the other hand the optimisation loop is apart from asymmetric arrangements, technological requirements etc.

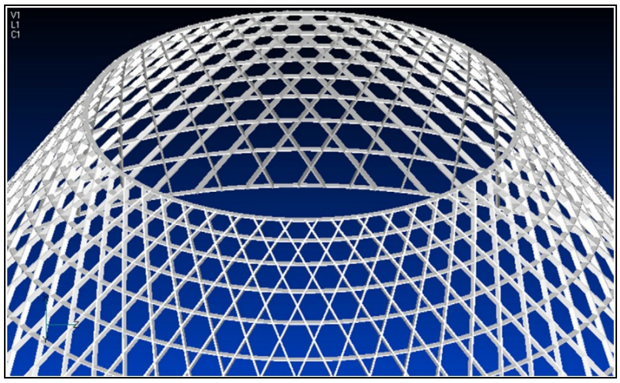


FIG 8. Lattice shell structure [1]

2.2. At developed cylindrical space structure

The described preliminary study starts with a plane model of the curved structure. This shall suspend the better understanding and a personal sensitivity beyond mathematical equations.

The frames behind the main landing gear are the interesting part of the fuselage structure. These represent a high loaded area, especially in the manner of lateral inertia forces. Hence the 2Δp pressurisation, the touch down and the vertical gust in level flight were decided as exploited static load cases – simplified, decoupled, superposed.

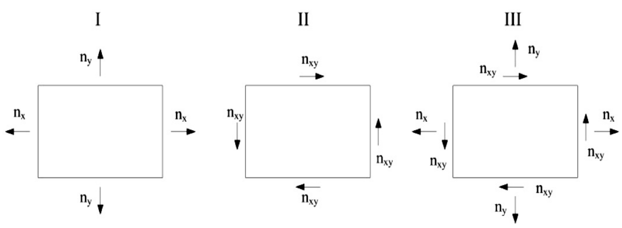


FIG 9. Loading conditions

FIG 9. is showing the considered loading conditions. All loads are effective in the plane. In a first step a homogenous isogrid framework was loaded with a shear load, see FIG 10.. The result is a constant deformation and load transmission. On this way the variations were investigated for helical angles, critical loads in strait rods, framework pattern or provided contours. The overall constant is the gross area of the single cells.

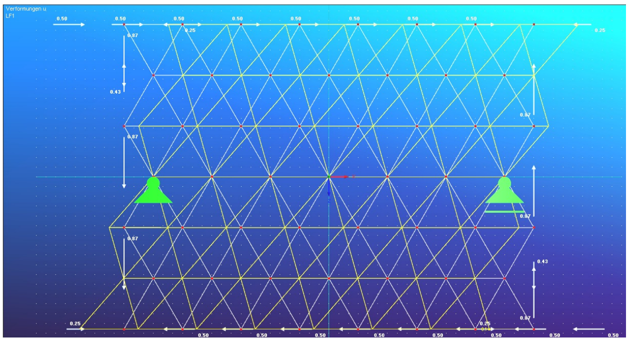


FIG 10. Homogeneous isogrid under shear inside a plane

Using the analytical parameter study several structural as well as geometric findings are realized:

- Equilateral triangles show the largest gross area but also the largest net area regarding cord width
- Single rod forces strongly depend on the range of load cases. An orientation beside the isotropic character of equilateral triangles is recommended.
- It is assumed that one regular section is used for every rod. Thereby mainly compressed rods shall be the shortest of the three types.

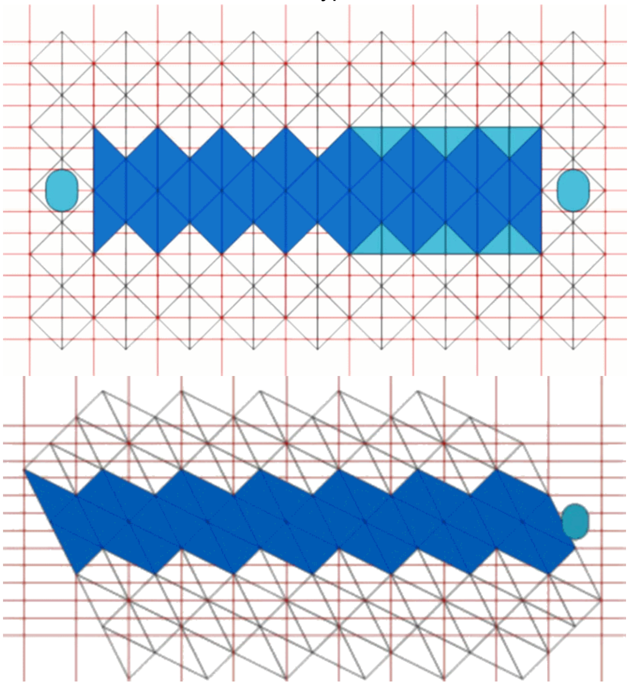


FIG 11. Geometrically integration of the framework
top: oriented at surrounding and rod loads
bottom: determined by rod loads

In a second step the six centre bars are extracted. The result is an inhomogeneous deformation with local increased but regular rod forces. Therefore two ambitions exist. Close to the homogeneous pattern for windows there could be a request of luxury specials. Another point of view is the permanent need of more suitable reinforcements for large cut outs. So a first look at such a configuration is shown in FIG 12..

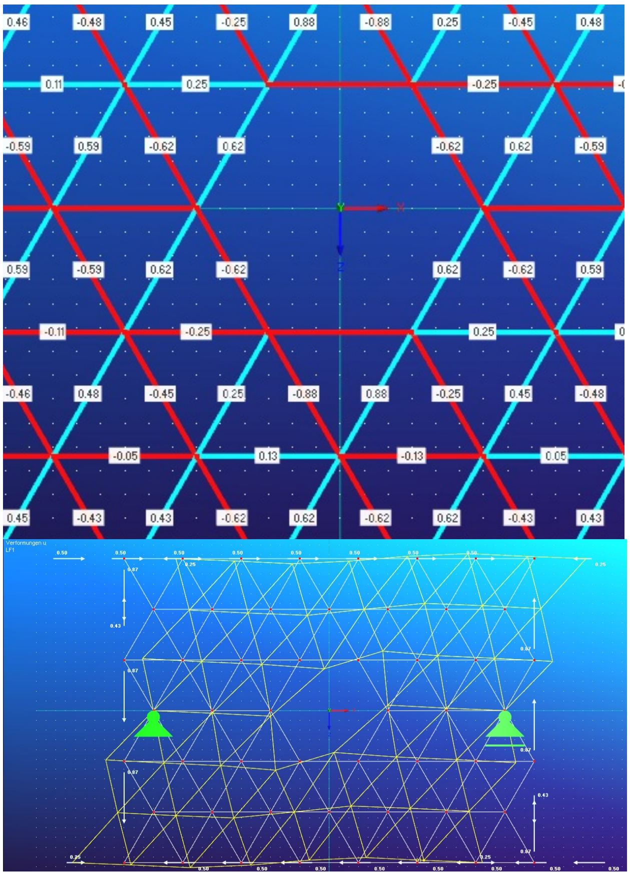


FIG 12. Inhomogeneous isogrid inside a plane, local increased forces

3. TOPOLOGY TRANSFORMATION

3.1. Conventional design

For the introduction of an unconventional design the inspiration by an engineer's mind is one way to find a suitable integration and structural transformation. Well known openings in an aeroplane fuselage give some ideas how it might work, e.g. FIG 13.. In addition to the reinforcements of the frames and stringers a huge local thickness increase is used to handle the reacting stresses and strains.

Top left: upper corner, longitudinal load transfer

Top right: ditto, circumferancial transfer

Left: lower corner, cut frame work of floor joint

FIG 13. Structural surrounding of a passenger door

3.2. The considered partial model

On the basis of the autonomous window structure (see 2) and conventional principles of load introduction the transformation between the topologies challenges the investigations enormously. The shell curvature is an important reason for it. In addition the topology change includes some stairs of eccentricities especially for the different stiffeners each.

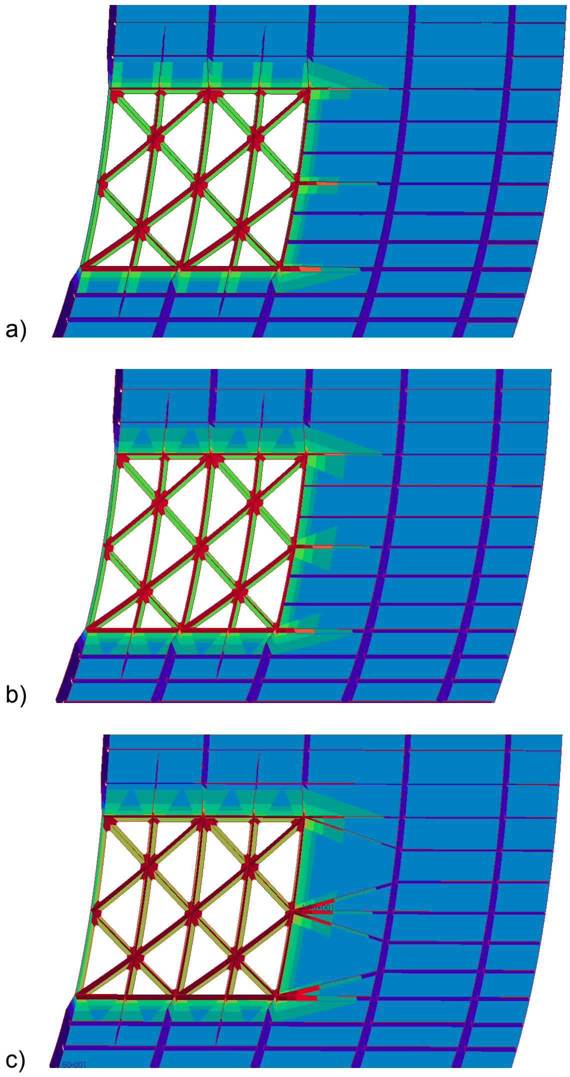


FIG 14. Topology approaches by derivation from a conventional opening design, thickness plot
a) and b) with a different way of load distribution by a cord
c) an alternative bridging for stringer loads

The size of the chosen model bases on the dimensions of the framework. To see the reactions in the fuselage and to keep the FE-model practical the model was enlarged. Three frame fields were completed in the flight direction. And four stringer fields are added in the circumferential direction each. The fields next to the framework are used to design the change of the topologies.

The proposed material distribution orients at the reserve for static strength. So the considered loads lead lo a quasi homogeneous skin, which is a little bit weaker in the longitudinal direction. However the approval of plate buckling requires a higher stiffness. Finally the proportional increased thickness shows a lay up of $(45_3\ /90_4\ /-45_3\ /0_1)_s$ with a theoretical thickness of 2.86mm. Thereby 0° is oriented in the longitudinal direction. For the transition area the rate of ±45° layers arises, because the load transformation shall prepared. An UD stack is strictly assumed inside the framework. The framework is modelled with shell elements too. At first the cord amounts 6mm and the web 10mm in thickness. Small variations are considered.

3.3. Loads and boundary conditons

For the first steps of the analysis the number of loads is strongly limited. These shall characterise the behaviour of such a topology in different ways. That means two basic loads for a shell near the wing root are selected, pressurisation and the vertical lateral force onto a fuselage take place.

- Pressurisation, FIG 15. a)
- Touch down impact (transverse force → shear load onto a fuselage side panel), FIG 15. b)

The boundary conditions inside the FEM-model are set so simple as possible, providing fast first impressions of the partial adapted structural variants. For the internal pressurisation the boundary conditions result out of the symmetry conditions. The loads which are introduced by the window panes are taken over by the cords of the framework, FIG 16.. Every other element being part of the skin is charged with the regular fuselage pressurisation.

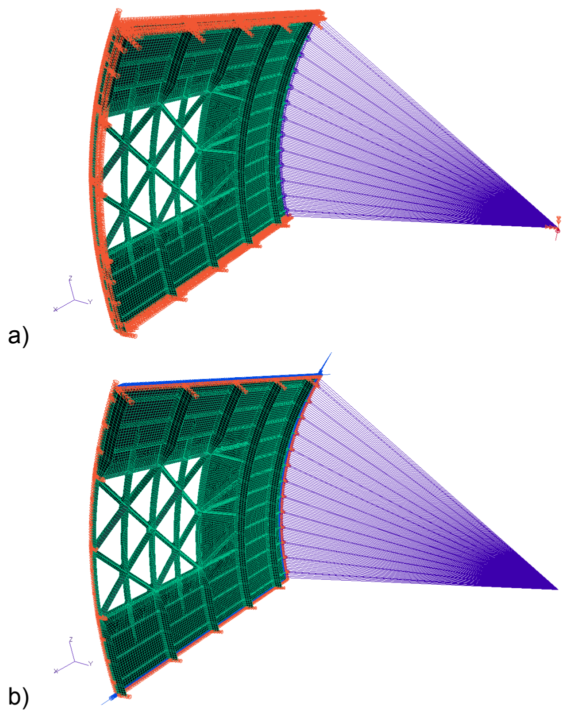


FIG 15. Boundary conditions and loads
a) pressurisation
b) homogeneous shear on a ‚mandrel'

For the shear load the boundary with the framework is blocked in the circumferential direction. That is why to reduce the disturbances out of a directly shear loaded framework. The other three boundaries are just blocked in the radial direction. An ideal typical surrounding is simulated in absence of more detailed information as well as with a high invariance for comparative analysis.

Following load cases are analysed:

- LC1 2 Δp = 2·600mbar
- LC2 Nxy = 220N/mm
- LC3 1.5Δp = 900mbar
  Nxy = 220N/mm

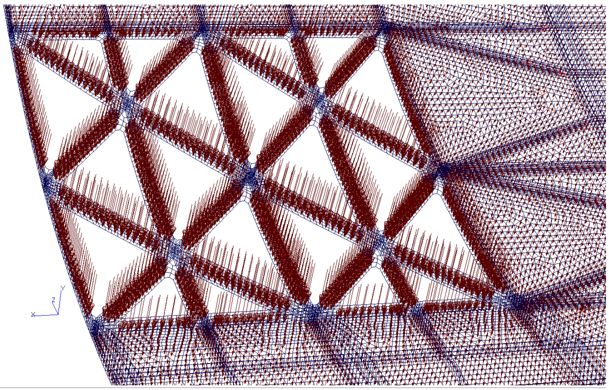


FIG 16. Partial pressurisation load, window frames suspend the pane loads

3.4. First results

Note the reference model is designed reverse from a series panel made of aluminium, E=70,000MPa assumed. In opposite to this the substituted framework and also the orthotropic bays are modelled with CFRP behaviours of a usual prepreg material for VTPs – $E_{||}$≈130GPa, $E_{\perp}$≈9GPa and G≈5GPa. The unidirectional loads inside the framework lead to this course of action. Every direct comparison with the reference is strongly limited therefore- But a basis exists to study essential challenges at the state of the investigation.

a)

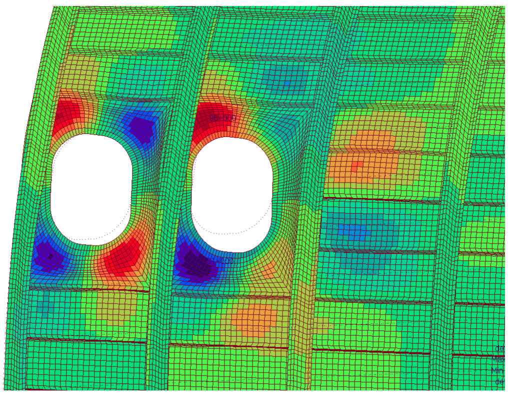
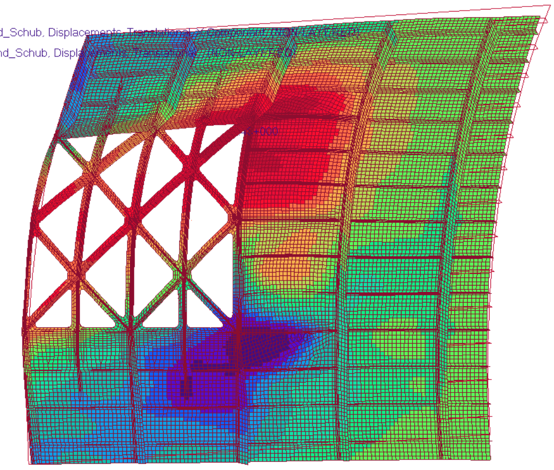


FIG 17. LC3 (superposed) – radial displacements

Local effects of conventional windows are more globalised in the case of a panoramic window; see FIG 17. and FIG 18.. That is an advantage at longitudinal borders, but at the same time the structural disturbances increase around the large corners. The framework provide a second homogeneous structure beside the conventional bays.



b)

FIG 18. LC3 (superposed) – radial displacements

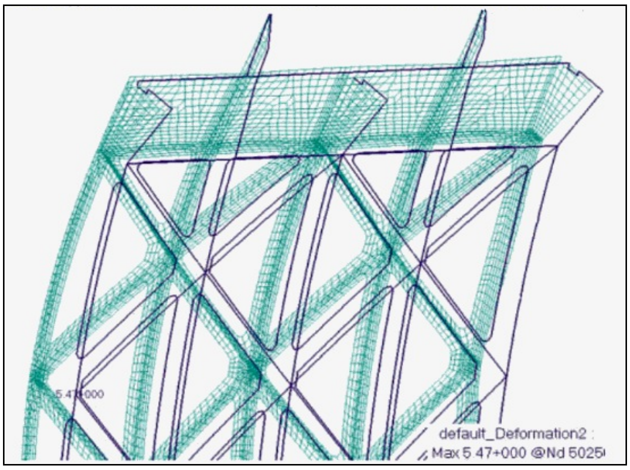


FIG 19. Deformation plot for 2Δp

The radial displacement by pressurisation characterises a similar behaviour for the longitudinal boundary. FIG 19. shows the larger displacement for the entire framework. Such an effect of lower local stiffness is well known for the surrounding of conventional windows too.

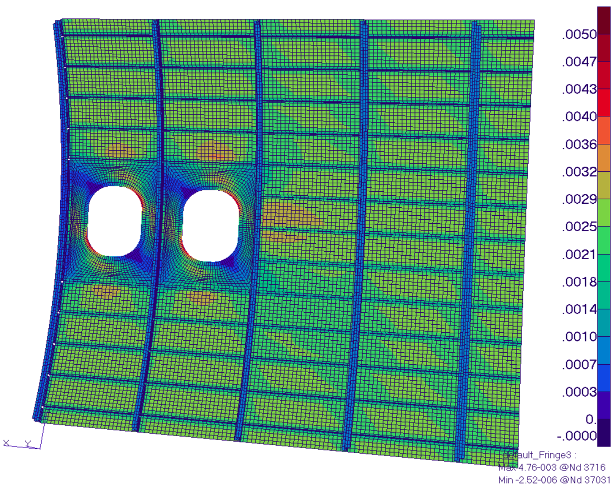


FIG 20. LC3 – max principle strain 2D (without window frames)

No excessive local load is indicated inside the framework as well as the surrounding. The total radial displacements exceed the referenced values. In addition the inconstant eccentricity affects the circumferential bending by changing the stiffener height, including the bars in the framework. These facts are expected regarding analytical abstract assumptions during the preparation of numerical analysis. But at the corner of the framework the deep span of disturbances surprises. This case is excluded by the analytical preliminary study. The simplified approach using a developed structure does not regard effects of eccentricity for this direction. The load balance is fulfilled for in plane loads. Hence a transmission of shear loads into the bounding frames is expected on a short way.

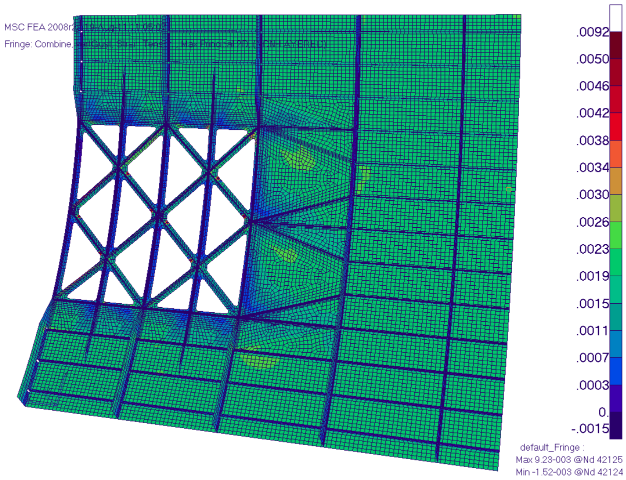


FIG 21. LC3 – max principle strain 2D

The reference model as well as the model including the new approach are loaded identically. Both characterise the LC3 as the most critical one for the three decided load cases. The nodal strain distribution is used in the imaged fringes as a common way of interpretation for FRPs. The extreme maximum principle strain, borders of the range, value perceptible higher values for the framework panel. But the same strain level of about 0.2% can be indicated in the area of the regular bays inclusive the frames, ≈0.1%, both. The more detailed view leads to several local peaks. These are the tasks for the future investigation.

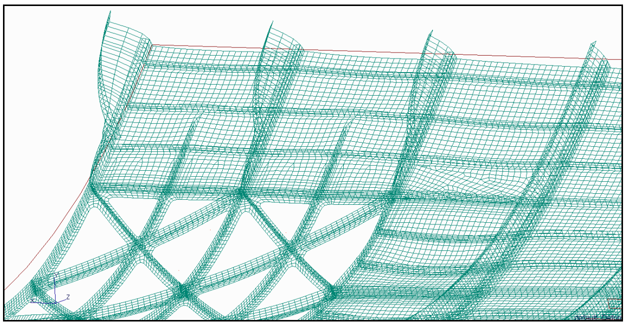


FIG 22. LC1 – frame torque a secondary load, arising by decoupling of the frames

In the case of single shear load, LC2, the cords of the framework show the similar value of maximum principle strain like the smallest radius of the conventional window corner. It amounts about 0.4% for the ultimate load. This encouraged the decided course of action. Note, the modelled reference structure is not exact at the same position like the used internal forces.

Systematic disturbances like shown in FIG 22. are intensified by the local decoupling of the frame sections. Be care with the interpretation of this figure, because there are used boundary conditions for sectors instead of closed frames. This behaviour of unsymmetrical frame section like a Z-frame is well known and it is passed by the use of an imaginary I-frame.

4. VISIONARY BUSINESS CLASS

4.1. Orientation by windows – design space

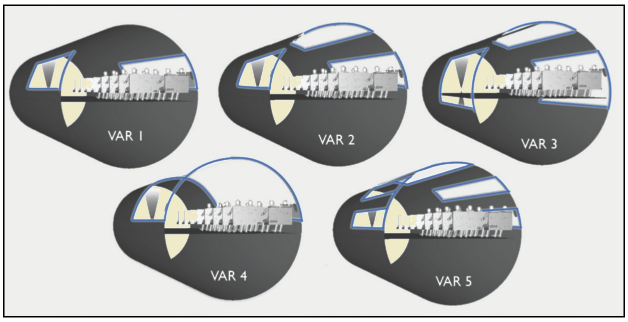


FIG 23. different ranges of transparency

Here in FIG 23. more or less excessive transparency areas are shown. The statements of the personal request, see above, lead to an important direction. One point is the felt safety, which expresses the balance between adventure by walking through the clouds and fear to fall down or to sit in a too fragile structure. Nevertheless everybody likes to see through the dome. So variant 2 was decided for the interieur example.

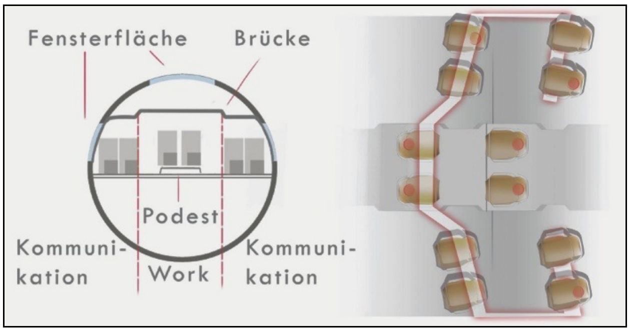


FIG 24. Seat package

The outer chairs face the windows, beeing turned some degrees. So it supports an impressive view for a straight seating passenger. The middle column arises a bit above the floor to look downwards similar to the side chairs.

4.2. Response fort the structure

In conclusion the opportunity of the structural approach can not support the desired view. Neither in the CAD made imaginations nor in the pure mind it is able to agree with the provided division of the panorama. So the number of helical angles is decreased and the distance between quasi parallel rods is increased simultaneously. Additionally the rod section scales proportional to the distances to keep the balance with the required strength. This geometric adaptation is not proven yet.

FIG 25. rear view

If a redistribution of the material is suitable to handle the service loads, then the design of window panes arises to a much higher importance. The structural analyses shown above are strongly associated with the dimension of the transparent area of common panes. That is way the design study consider suspending cords to complete the support at the boundaries. But it is not recommended in the point of ergonomics or esthetical worth.

5. CABIN WINDOWS – PANES

5.1. Mass to young's modulus ratio

A maximum displacement beyond the loft-line is one aspect of larger single panes. The reference for this part of investigation is given by the specification of an Airbus A340. The regular excess amounts to 3.5mm for 1Δp. The allowed displacement is assumed with 4.2mm in combination with the countersunk installation of the outer pane.

That describes the typical behaviour of windows made of plastic. Using this agreement it should be discussed about alternative classes of pane materials. So FIG 27. gives a short impression of more or less suitable materials, which are used in similar applications.

Material	E (in MPa)	ρ (in g/cm³)	R_m ($R_{flexure}$) (in MPa)
Acrylglas, PMMA	3,000	1.2	78
Luran 33100	3,800	1.8	75
Kieselglas (SiO2)	70,000	2.2	90
Spinel ($MgAl_2O_4$)	277,000	3.6	*170*
Alon	323,000	3.7	*700*

TAB 1. Selection of transparent materials

The table bases on the estimation of using the displacement of a round plate. It shall characterise a similar situation like a silhouette of an oblong hole suspended plate with 275mm in width (L) and 375mm in height (H). The area of the circle is so large as the window pane. It is reduced by a band of about 15mm, which is supported by the seal.

Using the called assumptions in simple formulas:

$$A_{Ref} = 2 \cdot \pi (R - l_{seal})^2 + \ldots \qquad (1)$$
$$\ldots\ldots\ldots + (L_{pane} - 2 \cdot l_{seal}) \cdot (H - 2 \cdot R)$$

$$r_{equ} = \sqrt{\frac{A_{Ref}}{2 \cdot \pi}} \qquad (1)$$

$$f = w_{max} = 0.696 \cdot p_o \cdot \frac{r_{equ}^7}{E \cdot h_{pane}^3} \qquad (2)$$

$$\sigma_r = \sigma_t = 1.24 \cdot p_o \frac{r_{equ}^2}{h_{pane}^2} \qquad (3)$$

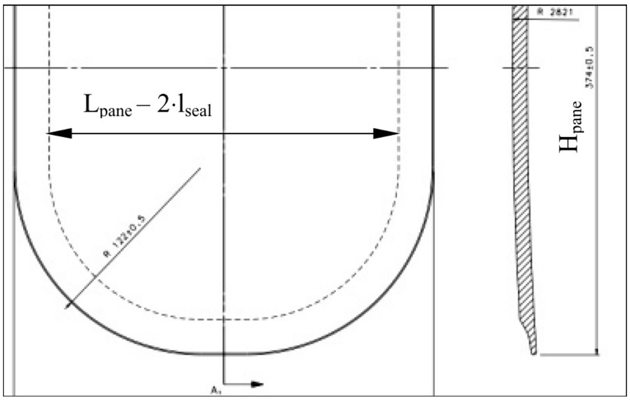


FIG 26. Detail of a window drawing

For estimation the dimensions, loads and boundary conditions can be described as follows.

- $L_{pane} - 2 \cdot l_{seal}$ = 245mm
- $H_{pane} - 2 \cdot l_{seal}$ = 375mm
- A_{Ref} ≈ 66400mm²
- r_{equ} = 145mm

The circle plate is hinged supported. It is loaded by normal pressure with two levels, 1·Δp and 2·Δp. The pressurisation of the fuselage, Δp, is assumed with 630mbar.

Material	$h_{min}(f_{max})$ (in mm)	$m(f_{max})$ (in g)	$h_{min}(2 \cdot \Delta p)$ (in mm)	$m(S_{max})$ (in g)
Acrylglas, PMMA	12.1	1012	6.7	563
Luran 33100	11.1	1415	6.8	868
Kieselglas (SiO2)	4.2	655	6.2	968

Material	$h_{min}(f_{max})$ (in mm)	$m(f_{max})$ (in g)	$h_{min}(2 \cdot \Delta p)$ (in mm)	$m(S_{max})$ (in g)
Spinel ($MgAl_2O_4$)	2.7	674	4.5	1147
Alon	2.5	660	2.2	582

TAB 2. Estimations of thickness (h) and mass for several materials as well as classes of materials

Together the TAB 2. and the FIG 27. lead to interesting interpretations. But at first a introduction of the curves and markers is needed. One the one hand there are shown curves, which describes hypothetic materials with several densities changing the Young's Modulus continuously. Here the E is directly associated with the stiffness requirement. The necessary thickness, height of plate called h, to fulfil the goal times the reference area times the density gives the ordinate value. The blue line only describes the thickness to meet the maximum allowed displacement, drawn on the secondary ordinate.

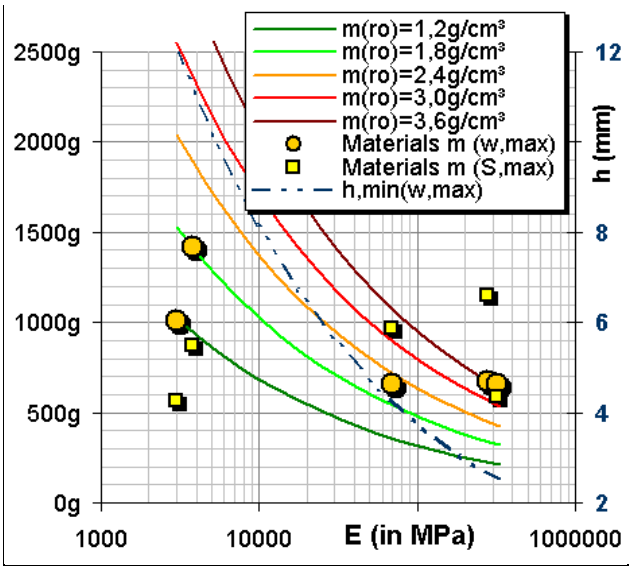


FIG 27. Several examples of transparent materials, shown in a field of iso-density lines

On the other hand the markers describe the calculated values for a selection of materials. Circles represent the minimal weights to meet the stiffness. Rectangles are the lower limits by the material strength. Note, the strength requirement correspondents with the higher load level of $2 \cdot \Delta p$.

The most suitable material is characterised by the lowest need of thickness for both requirements. By enlarging the area the stiffness gets a higher influence than the strength. In consequence the amorphous materials arise to be more interesting in the future.

6. SUMMARY

During the preparation of a research theme several preliminary studies are made. These consider the ambitious question about the possibility as well as the suitable configuration of an panoramic window aeroplane. A wide range of aspects is spanned, but many requirements will arise in the future too. Just the results encourage the ambition to start the more detailed structural investigations.

Using highly abstracted analytical models the first numerical investigation is supported right. Several expectations are confirmed as well as completed by the FEA. Especially the design challenges of the integrated framework inside a plate structure are indicated.

The conceptual approach also regards the use for passenger journeys. Hence the investigation of the interieur benefit leads to non marginal increased structural requirements. That is why enlarged window panes are an important partial goal. If the introduced concept, which uses unloaded transparent panes, is suitable for such a high ambition, is not clear yet. Alternatively the interieur proposal must be reworked or the concept of loaded panes shall be pushed.

7. REFERENCES

[1] G. Totaro, Z. Gürdal; "Optimal design of composite lattice shell structures for aerospace applications" Aerospace Science and Technology 13 (2009) S.157–164

[2] Munroe, J.; Wilkins, K.; Gruber, M.; "Integral Airframe Structures (IAS) – Validated Feasibility Study of Integrally Stiffened Metallic Fuselage Panels for Reducing Manufacturing Costs"; Boeing/NASA CR-2000-209337

[3] Birke, M.;"Ausschnitte in Flächentragwerken - Störung oder Bestandteil quasihomogener, skalierbarer Bereiche" – Großer Beleg; Dresden University of Technology 2008

[4] Gruner, J.;"Ausschnitte in Flächentragwerken - Störung oder Bestandteil bezogen auf Übergänge zwischen quasihomogenen Bereichen" – thesis for a degree; Dresden University of Technology 2008

[5] Zwiebler, U.: "Entwurf eines Interieurbereichs für ein Passagierflugzeug unter dem Aspekt der Nutzung neuer Gestaltungsmöglichkeiten der Fenster" – Great Study Paper; Dresden University of Technology 2009

[6] Ulbrich, S.; "Numerische Abschätzung der erreichbaren Qualität experimenteller Simulationen an Rumpfschalen mit großen Öffnungen" – thesis for a degree; Dresden University of Technology 2010